

Experimental measurements of upward flame spread on a vertical wall with external radiation

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Abstract

The overall objective of the project is to gain an understanding of the flame spread phenomenon under simulated surrounding fire conditions. In this phase of the project, emphasis is placed on obtaining experimental data for upward flame spread with applied external radiation on practical wall materials. A second phase (not yet reported) is the development of a numerical flame spread model and the experimental results presented here will be used for comparison with model predictions. Flame height, and in some cases pyrolysis height, were recorded as functions of time for 120 cm × 30 cm samples; and these data were used to quantitatively investigate the effect of external radiation on several materials. Infrared heating panels were used to supply radiant fluxes of up to 15 kW/m² to the sample. Many wood-based materials do not exhibit flame spread to the top of the sample when ignited without applied external flux. With moderate levels of external radiation (5–10 kW/m²), many of these materials sustained flame spread to the top of the sample. With increasing external radiation levels, flame spread was also more rapid. A comprehensive series of tests was run on particle board to investigate the effect of igniter strength, preheat of the sample, and sample thickness. Igniter strength was not a significant factor and did not cause the flame spread to be sustained; the effect of preheat, even at moderate levels of radiant flux, was important; and sample thickness had a slight effect, with thicker samples burning slower. Total heat feedback to the sample was measured and the maximum values for various samples are reported. Experimental data obtained in this project will be used to aid in the development and validation of a numerical flame spread model. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Upward flame spread; External radiation; Flame height

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Nomenclature

Symbols

c	specific heat
k	thermal conductivity
N	number of data points
\dot{q}	heat feedback flux to sample surface
ρ	density
T	temperature
V	velocity
x	height measured from the bottom of the fuel sample
δ	characteristic length over which the heat feedback is important

Subscripts

a	ambient conditions
b	burnout front
er	external radiation
f	flame front
p	pyrolysis front

1. Introduction

The importance of upward flame spread stems from its ability to occur rapidly and present a significant fire hazard. Some of the early researchers of upward turbulent (large-scale) flame spread conducted basic experimental work and developed theoretical models [1–3]. The experimental part of these investigations did not include external radiation sources. In post-flashover rooms, radiant flux levels may reach 100 kW/m² [4]; even in pre-flashover enclosure fires, significant amounts of energy are radiated to other walls which have not yet begun to burn. It has been observed that certain materials which do not sustain upward flame spread in the absence of external radiation flux (for example, wood), do allow the flame to spread when assisted by an external radiation source [5]. It is also expected that materials which normally display upward flame spread will exhibit significant enhancement in flame spread and fire growth in the presence of external radiation [6,7]. Some of the standard tests, such as ASTM E 162 for horizontal flame spread [8] and ASTM E 648 for downward flame spread [9], indicate that materials which are normally considered safe may behave unacceptably under an actual fire situation.

External radiation affects upward flame spread in two ways. First, the radiant heat flux adds to the heat feedback from the flame and causes the yet-unburned surface of the sample to heat up to the pyrolysis temperature more quickly. Second, over the surface area already burning, external radiation increases the mass loss rate of the sample, and in turn causes higher flames. Theoretical work of previous investigators

provides insight into the relative importance of these two effects on upward flame spread. The approximate expression suggested by Thomas and Lawson [10] for the steady-state velocity of the pyrolysis front is

$$V_p = \frac{4(\dot{q}'')^2 \delta}{\pi k \rho c (T_p - T_a)^2} \quad (1)$$

In this equation, \dot{q}'' is the heat feedback to the sample surface, δ is a characteristic length over which the heat flux acts (and may be estimated by $x_f - x_p$, the flame height minus the pyrolysis height), k the thermal conductivity of the sample, ρ the sample density, c the specific heat, T_p the pyrolysis temperature, and T_a the ambient temperature of the sample. An increase in external radiation increases the heat feedback, which in turn increases the flame spread velocity. Since the heat feedback term is squared, the flame spread velocity will have a strong dependence on the external radiation. The increase in mass loss rate causes the difference between the flame height and the pyrolysis height to be higher (the increased mass loss rate relates to an increased energy release rate, which corresponds to larger flames), and also results in a higher flame spread velocity [2].

The present program was undertaken to provide basic understanding of upward flame spread with applied external radiation. In addition to examining the effect of external radiation on flame spread, other parameters such as line burner strength and preheat time were investigated. The broad database of experimental measurements made on practical materials may be useful to others for model validation and may suggest useful parameters for flammability ranking.

2. Experimental apparatus

A schematic of the upward flame spread facility at the Pennsylvania State University is shown in Fig. 1. The sample materials burned in the apparatus were 30 cm wide, 120 cm high, and of various thicknesses. The samples were installed such that the front surface was flush with the larger, outer panel of inert material. No backing material was used with the sample materials (except for the cotton textile). Kokkala *et al.* [11] have shown that the type of backing or lack of backing will affect the upward flame spread rate. On either side of the panel of inert material were water-cooled copper side shields angled forward at 45°. These shields served to block extraneous radiation from the panels and minimize cross-flow to retain the two-dimensionality of the flame spread. A line burner was used to ignite the lower edge of the sample. The burner was fueled with propane, and by varying the flow rate of the propane, the line burner strength may be set at values from 3.6 to 18.5 kW/m.

Two electric powered infrared heating panels were angled towards the sample material to supply a heat flux which simulates the sample being burned in a room in which other walls are on fire and supplying radiant energy. The panels reach temperatures of 815°C and produce a maximum radiative flux of 63 kW/m². In the arrangement used for the series of tests, the vertical top to bottom centerline of the panels face was 30 cm from the face of the sample and inert backboard; the panels

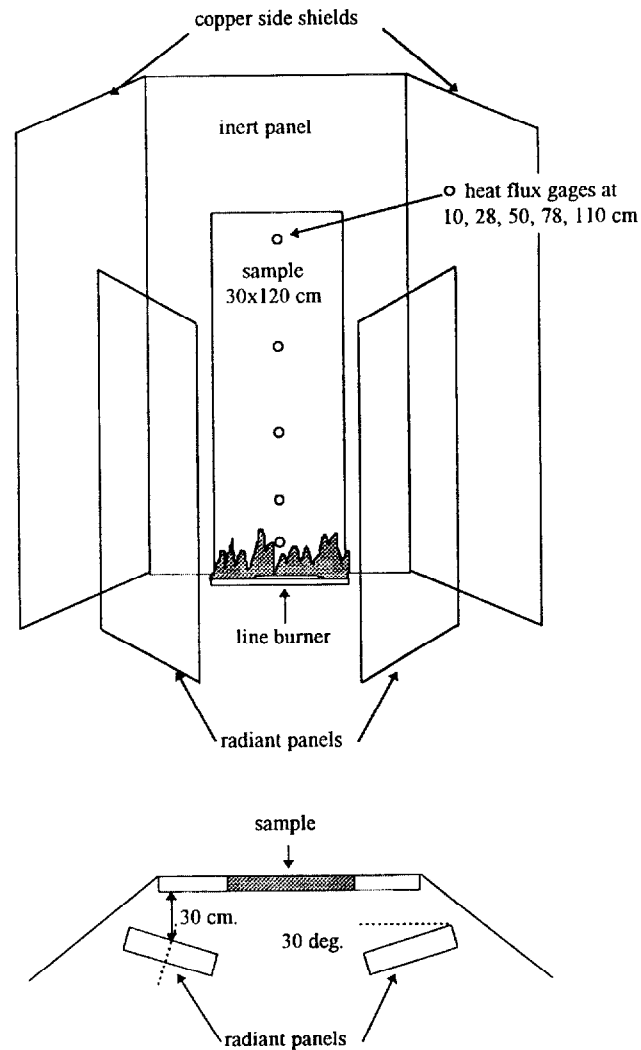


Fig. 1. Experimental upward flame spread apparatus — front and top view.

were angled 30° with respect to the sample; and a 30 cm gap between the radiant panels was maintained to allow a view of the full sample width. The radiant panels had nearly constant heat flux distribution horizontally, but the vertical distribution varied more significantly. The radiation level dropped to about 66% of the average at the top and bottom, and increased to 118% of the average at the center. Average heat flux over the entire sample area is used to denote the level of external radiation. A maximum average flux of 15.1 kW/m^2 can be supplied to the sample. In order to vary the heat flux to the sample, a silicon control rectifier was used to control the voltage and current to the panels.

A typical test involved turning the radiant panels on until they reached steady state. During this time, the sample material was shielded from the radiation. Nearly simultaneously, the shield was removed and the line burner placed in front of the sample. The burn event was videotaped and by reviewing the tape, flame height as a function of time was determined. Flame height is measured from the base of the sample to the highest location of continuous luminous flame or the highest location of a luminous flame ball (separated from the continuous flame) larger than 5 cm. Ten frames over a time period of approximately one-third of a second were averaged for calculation of the flame height. The flame height measured for each of the flames fell within $\pm 15\%$ of the mean flame height. In some cases, pyrolysis front history (chosen as the location of darkening of the sample surface) was determined from the videotape. Only materials for which the surface color change could be visually detected have pyrolysis front location data presented. The pyrolysis front tended to be smooth and visual inspection was used to select an average pyrolysis height based on single frames of the burn event.

Total heat feedback to the sample surface was measured during burn events using water-cooled Gardon circular heat flux gages. The gages were installed at heights of 10, 28, 50, 78, and 110 cm on the centerline of the sample material. Temperature information reported for these experiments was obtained from K-type thermocouples that were slightly embedded (to shield them from radiation) into the sample surface. Thermocouples were installed on the front and back surfaces at the same heights as the heat flux gages were installed. Error associated with the thermocouples is insignificant and it is the installation method that greatly affects what the thermocouple is actually measuring. Only surface temperatures during the preheat or early stages of the burn event are reported and are not subject to the difficulties that arise when the sample surface is significantly consumed.

All of the test materials were stored in the laboratory and were subject to the variation in humidity that occur in a temperature controlled environment. The following descriptions are for the materials tested in the upward flame spread apparatus.

- Clear polymethylmethacrylate (PMMA) (3.2 mm thick), known by the trade name Plexiglas G and manufactured by Rohm and Haas.
- Three thicknesses (9.5, 15.9, 25.4 mm) of Douglas Fir particle board made by Georgia Pacific.
- Fire-retardant plywood (12.7 mm) and untreated plywood (12.7 mm) came from the material bank at NIST and are pine with CD surface quality ratings.
- Poplar (19.0 mm) was a solid wood obtained locally.
- Cotton textile was a tan-colored broad cloth material with a weight per unit area of 0.247 kg/m^2 . The cloth was stapled onto a backing of fire-retardant plywood.
- Hardboard (3.2 mm) with both sides tempered (tempering results in smoothed/hardened surface, typically at least one surface of hardboard is tempered) was tested. Hardboard is sold under the trade name Masonite.
- Grey laminated cardboard (6.3 mm).

The flame tip and pyrolysis front location data shown are for single-test runs. When possible, two tests at a particular condition were run to obtain an indication of the

variability associated with flame spread measurements from sample to sample. An RMS deviation was calculated according to the following equation:

$$\text{RMS deviation} = \left[\frac{\sum_{t=1}^{t=N} [x_{f,\text{test a}}(t) - x_{f,\text{test b}}(t)]^2}{N} \right]^{1/2}$$

Flame heights measured at identical times from ignition to the time when flames began to recede were used in the calculation. The difference in flame height between tests were squared, summed, divided by the number of data points, and then the square root taken. The RMS error was 21.3 cm for plywood, 9.4 cm for particle board, 21.7 cm for hardboard, and 22.9 cm for poplar. No calculation of RMS deviation was made for cardboard, due to difficulties in obtaining sample material; or for cotton, due to difficulties in obtaining data in the short time for flame spread to the top of the sample.

3. Results

Several test parameters were varied to determine the effect on the rate of upward flame spread. In addition to testing different sample materials; external radiation, igniter strength, length of sample preheat, and sample thickness were varied. Tests will be classified as being sustained to the top of the sample or unsustained. For a test case to be considered sustained, the flame front and pyrolysis front must both reach the top of the sample and the flame front must precede the pyrolysis front. The results will be presented in the following section.

3.1. Effect of external radiation

Fig. 2 shows flame height versus time data for several materials. All of the plots have the same test conditions, namely, igniter strength of 18.5 kW/m (corresponds to a flame height of 28 cm), external radiation of 7.6 kW/m², and no preheat. PMMA (plastic) and hardboard (wood-based with binder) both exhibited sustained flame spread without external radiation, but the application of additional heat flux caused faster flame spread. Without external radiation, the other materials (all others are wood-based or cotton) do not exhibit flame spread to the top of the sample. Flame height data without external radiation is not shown in Fig. 2 because the flames do not spread much above the height of the line burner and the plots would only clutter the figure. With external radiation of 7.6 kW/m², various trends can be noted: particle board (15.9 mm), hardboard, cardboard, PMMA, and poplar show sustained upward flame spread; plywood shows an initial period of flame spread but the flames recede before the pyrolysis front reaches the top of the sample; and fire-retardant plywood (12.7 mm) and cotton textile show no flame spread. Since the cotton textile is a relatively thin material, the time scale of burning for this sample is much shorter than that for the other materials.

The cotton textile (broadcloth) was tested at various external radiation levels and the results are shown in Fig. 3. The textile was stapled onto a fire-retardant plywood

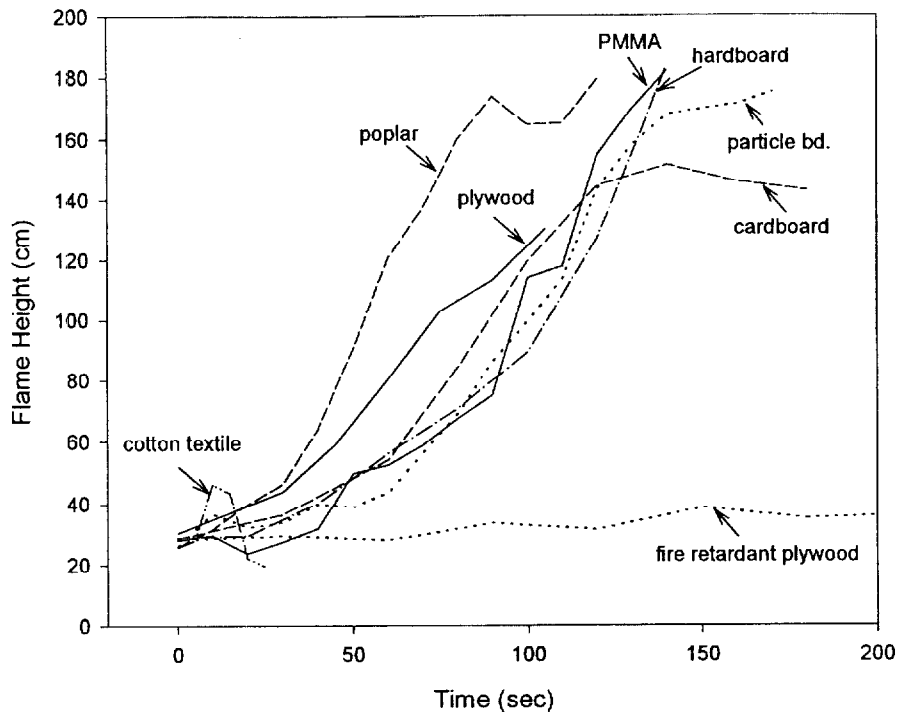


Fig. 2. Flame spread for various materials with external radiation of 7.6 kW/m^2 , igniter at 18.5 kW/m^2 , no preheat.

backing. The backing did not allow flame spread to occur on both sides of the textile and did not become involved in the burn event. At the lowest two levels of external radiation, no upward flame spread occurred. The cloth burned only over the area covered by the line burner flames. At a radiation level of 7.6 kW/m^2 , the flames spread partway up the material but died out before reaching the top of the sample. At the highest level of external radiation (13.5 kW/m^2), the flames very quickly moved up the full height of the sample. The pyrolysis front was difficult to measure because application of the radiant flux caused the material to begin to turn brown (char) simultaneously over most of the sample. Since the cotton material is relatively thin compared to other materials tested, it was completely consumed, and a well-defined burnout front was seen. (Burnout front is not reported for any other samples because these samples were relatively thick and the material was not fully consumed during the length of the upward flame spread event.) The burnout front was chosen as the lowest location on the sample face to be covered by flames. It was chosen based on a visual average across the width of the sample and on a single frame. In Fig. 3, the burnout front location as a function of time is shown for the sustained flame spread case at 13.5 kW/m^2 .

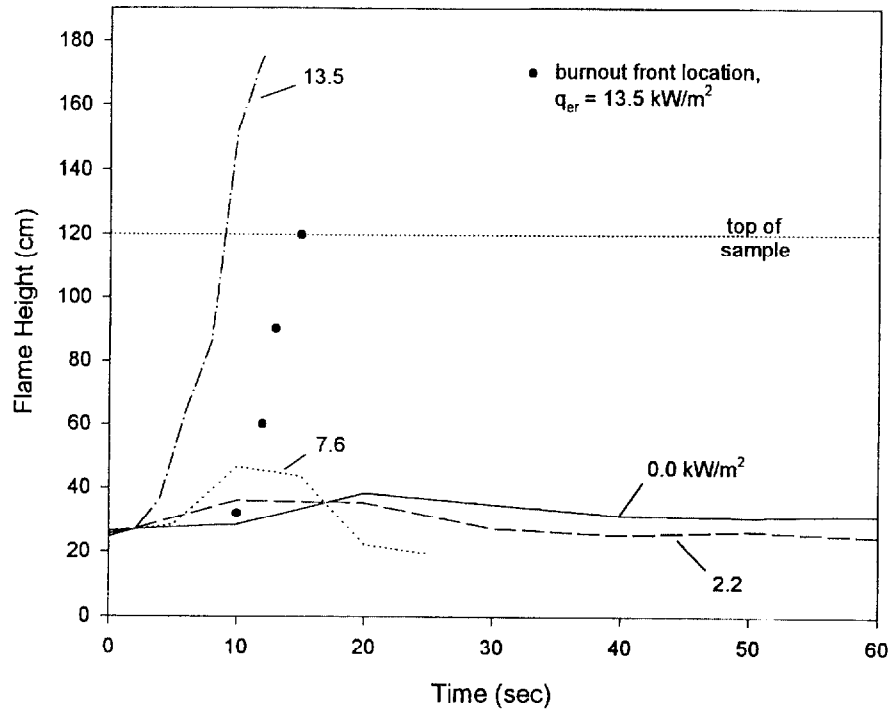


Fig. 3. Flame spread for cotton textile at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

In Fig. 4, experimental data for poplar wood are presented. The only test condition varied between these plots is the level of external radiation. Pyrolysis fronts were measured for each of the runs by noting a change in the color of the sample surface. The pyrolysis locations corresponding to tests run at 2.2 and 0.5 kW/m² are shown in the figure. For flux levels of 2.2 kW/m² and higher, the flame spread is sustained to the top of the sample. This is demonstrated in the figure by the pyrolysis front reaching the top of the sample. (The sample height is denoted in the figure by the dotted line at 120 cm.) Although the flames for the 0.5 kW/m² heat flux case reach the top of the sample, the pyrolysis front does not, and eventually the flames recede below the pyrolysis front.

Flame heights as a function of time for 15.9 mm particle board with igniter strength of 18.5 kW/m, no preheat, and various levels of applied external radiation are shown in Fig. 5. Pyrolysis front location as a function of time is also plotted to illustrate which of the tests exhibit sustained upward flame spread. For sustained upward flame spread, the flame front should stay ahead of the pyrolysis front, and the pyrolysis front and flame front should both reach the top of the sample. With external heat fluxes of 7.6 kW/m² or greater, the flame and pyrolysis front spread to the top of the sample.

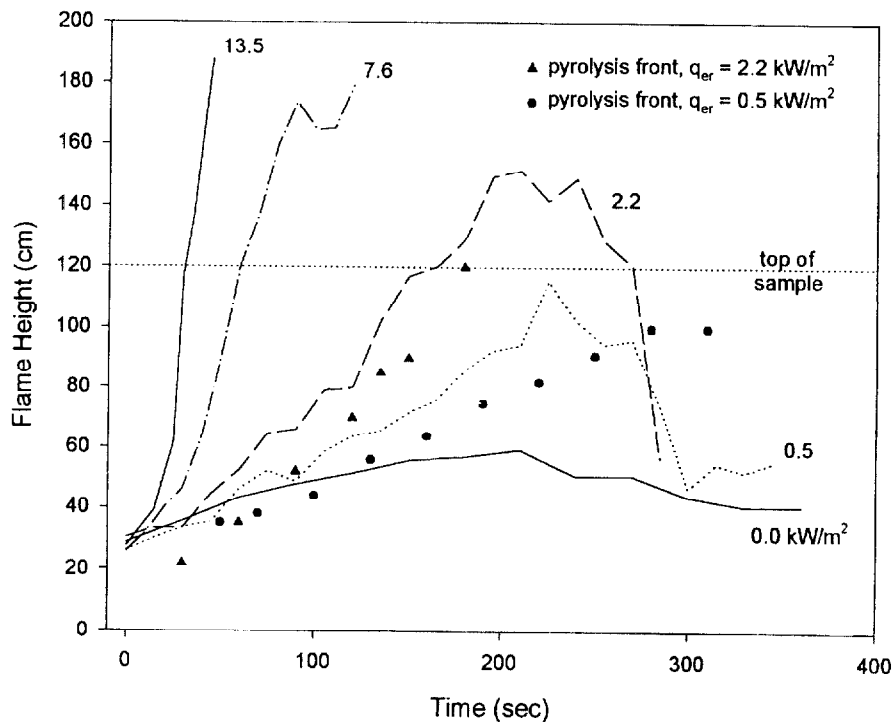


Fig. 4. Flame spread for poplar at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

This value is similar to the results obtained by Saito *et al.* [2] which showed that sustained upward flame spread on particle board did not occur until the critical flux level of 7.0 kW/m² had been reached. The particle board tested by Hasemi *et al.* [13] (see Fig. 5) exhibited sustained flame spread at 5.0 kW/m². With a sample height of 200 cm, the flame tip front and pyrolysis front reached higher levels than the present work which has a sample height of 120 cm. In addition to the effect of external radiant flux, some of the differences between the Hasemi *et al.* data and that of the present research may be attributed to variations in test parameters such as the igniter strength, preheat time, material composition and moisture content. Also recall that data being presented is based on average external radiation while the actual distribution varies significantly from being uniform. Preheating of the sample tested by Hasemi *et al.* may result in a lower level of heat flux being required for sustained flame spread. Above the critical flux level, the higher levels of external radiation caused faster upward flame spread. Two plots from previous works [2, 13] are also shown in Fig. 5. Again, the igniter strengths and material thicknesses differ from those of the present work, but the magnitude of the flame spread is in the same range as the data being presented.

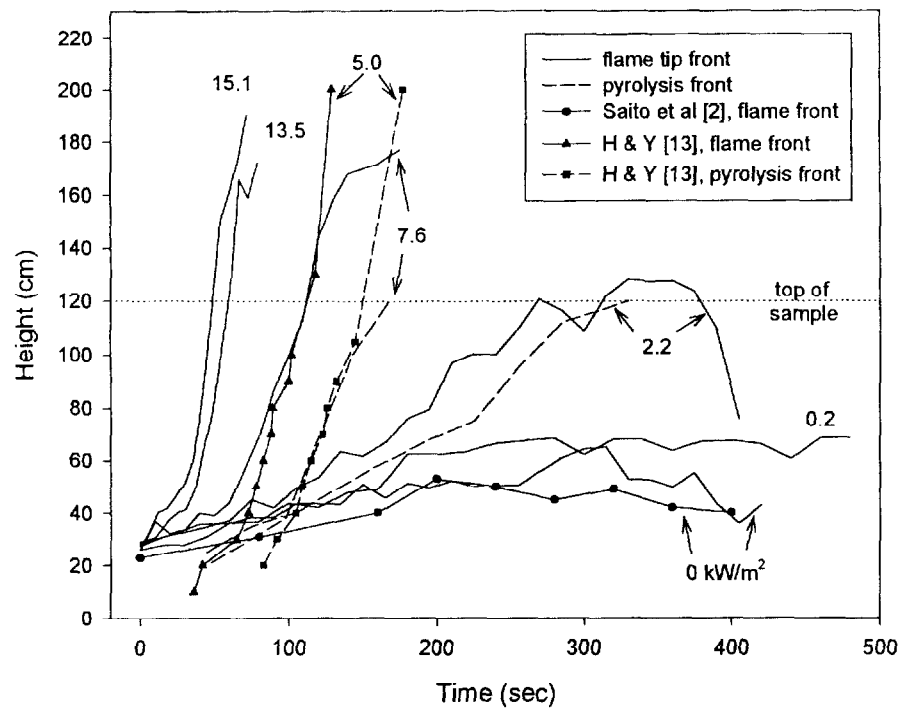


Fig. 5. Flame spread for particle board at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

Flame height measurements for plywood are shown in Fig. 6. For this material sustained flame spread almost occurred at 7.6 kW/m², and was definitely sustained at an external radiation of 13.5 kW/m² and above. Data from Hasemi *et al.*, also presented in the figure, show sustained flame spread for external radiation of 5.0 kW/m². The experimental procedures used by Hasemi *et al.* required the sample to be preheated and may result in sustained flame spread at lower applied external radiation levels.

The flame height results for hardboard at various levels of external radiation are shown in Fig. 7. As previously noted, flame spread was sustained to the top of the sample without external radiation, and the addition of radiation served to increase the flame spread rate.

For cardboard, an external radiation level of 7.6 kW/m² was required for the flame spread to be sustained to the top of the sample and, therefore, the critical flux required for sustained flame spread falls between 2.2 kW/m² (not sustained) and 7.6 kW/m² (sustained). Quantitative data for the flame height for cardboard at various levels of radiation are shown in Fig. 8.

In sustained flame spread, the velocity of the pyrolysis front or flame front should be constant or accelerating with increased time. The data presented is in the form of

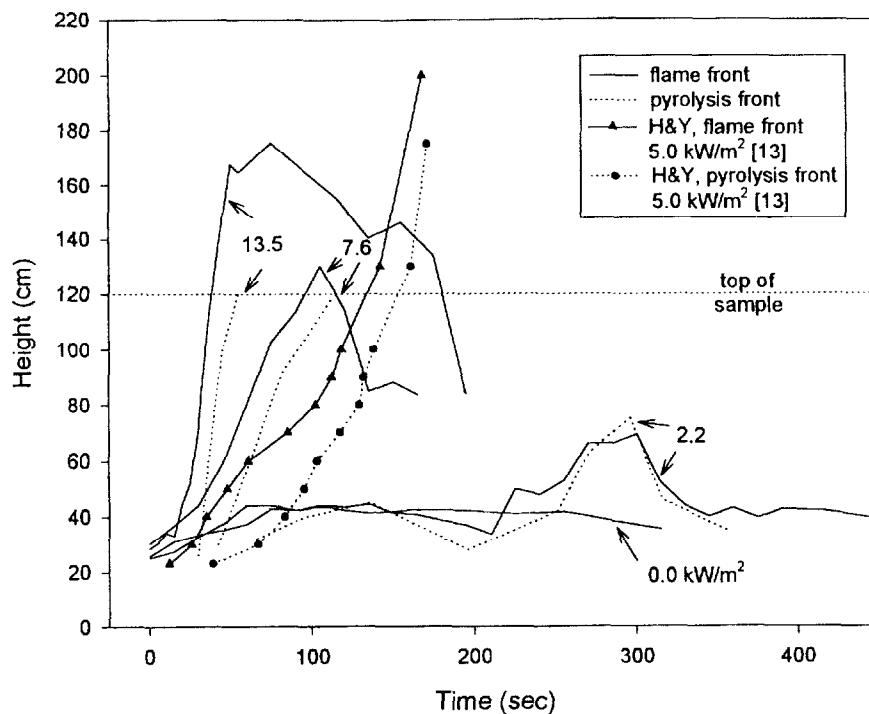


Fig. 6. Flame spread for untreated plywood at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

pyrolysis front or flame tip location as a function of time. Examining the slope of this data (dx_p/dt or dx_f/dt) gives an indication of the pyrolysis front velocity or flame front velocity. The general trend evident from the data is that increased levels of external radiation result in an increased slope of the pyrolysis front and flame tip front as functions of time. Several other test parameters were varied to determine their effect on flame spread.

3.2. Effect of igniter strength

In order to examine the effect of igniter strength on upward flame spread, the level of external radiation was held constant at 2.2 kW/m² for particle board samples with no preheat. Three levels of igniter strength were used: 3.6 kW/m (resulting in a flame height of 10 cm); 11.0 kW/m (flame height of 20 cm); and 18.5 kW/m (flame height of 28 cm). In Fig. 9, it can be seen that higher levels of igniter strength caused the flames to spread further, but did not result in sustained flame spread. Igniter strength is only a factor in the initial phase of flame spread, eventually the flame spread activity moves out of the region over which the igniter has any influence. Steady-state flame spread would not be expected to be significantly affected by igniter strength.

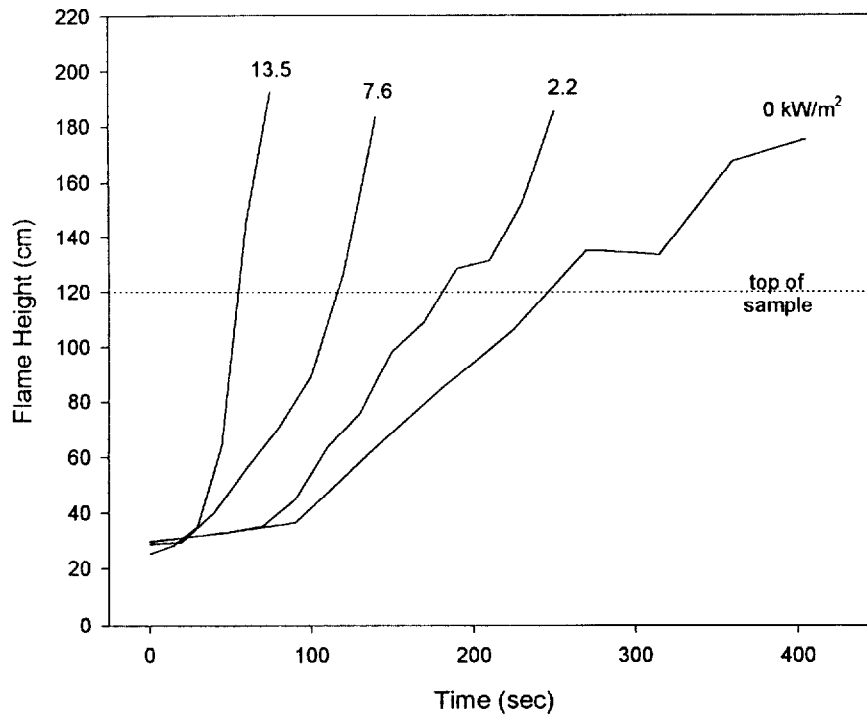


Fig. 7. Flame spread for hardboard at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

3.3. Effect of preheat

In Fig. 10, the effect of preheating particle board samples prior to ignition is examined. The preheated sample was exposed to a radiant flux of 2.2 kW/m² until the temperatures measured on the front and back surfaces of the sample were nearly constant. The average temperatures of the front and back surfaces were 142 and 76°C, respectively. Once steady-state conditions were reached, the sample was ignited. The average surface temperature of the non-preheated sample was 30°C when ignited. Enough energy must be supplied to the sample to heat the surface up to the pyrolysis temperature. Preheating the sample raised the surface temperature by over 100°C and, therefore, less time and/or energy was needed to achieve the surface temperature required for pyrolysis to begin. The preheated sample displays significantly faster flame spread than the sample which was shielded prior to ignition. A theoretical estimate of the effect of preheat on the steady-state spread rate of the pyrolysis front (equation presented earlier) shows the same qualitative trend as that seen in the experimental work. The term $(T_p - T_a)$ in the relation suggests that the smaller the temperature difference between the ignition temperature (T_p) and the initial temperature of the sample (T_a), the larger the pyrolysis front velocity will be. The slopes of

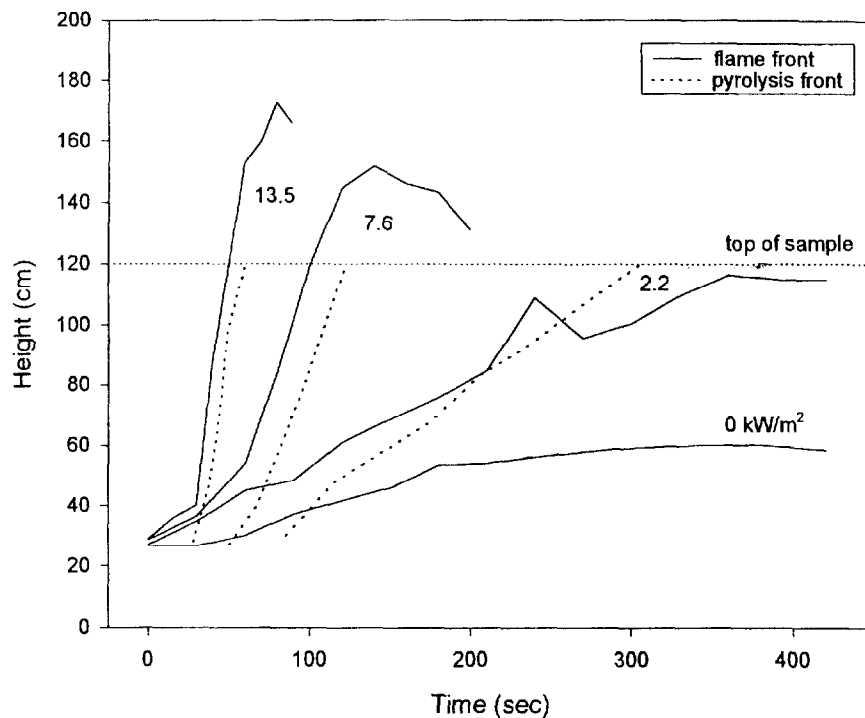


Fig. 8. Flame spread for cardboard at various levels of external radiation, igniter at 18.5 kW/m, no preheat.

flame tip and pyrolysis front locations as functions of time (corresponding to flame tip and pyrolysis front velocity) are larger for the case when the sample's initial temperature was raised due to preheating.

3.4. Effect of sample thickness

In Fig. 11, flame spread for several thicknesses of particle board (9.5 mm, 15.9 mm, and 25.4 mm) are shown. The particle board thickness used in all previous tests was 15.9 mm. With the application of 2.2 kW/m² (no preheat) external radiation, the flame spread is slightly faster for the thinner materials. Thermocouple measurements of the back surface temperatures for all three samples showed very little change from the ambient temperature over the time period of the burn event. Many common materials thicker than 1 mm may be assumed thermally thick [12] for the length of time typically associated with upward flame spread. The general equation for pyrolysis front velocity [Eq. (1)] is not a function of material thickness, but the experimental data shows a slight dependence of flame spread rate on material thickness, even for these thermally thick samples.

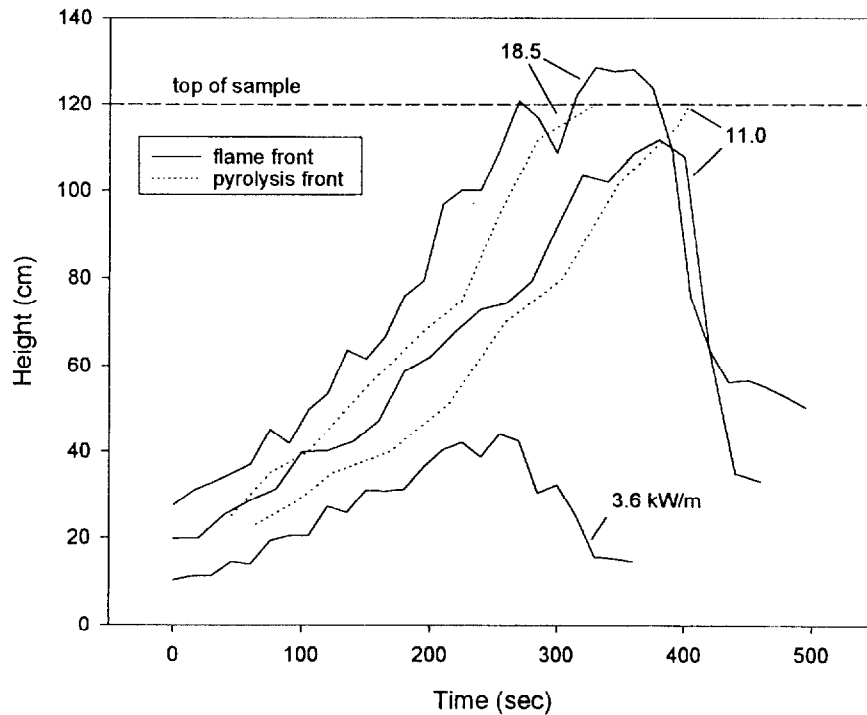


Fig. 9. Effect of igniter strength on flame spread, particle board, external radiation of 2.2 kW/m^2 , no preheat.

3.5. Total heat feedback

Total heat feedback at various heights along the sample face was measured. Representative cases are shown in Figs. 12–14. The heat flux gages initially showed some level of heat flux due to the radiant panels. Once the line burner was placed in front of the sample, the lower two gages showed immediate jumps in heat flux. As the flames spread up the sample surface, the gages mounted further up the wall received higher levels of heat feedback. In Fig. 12, the heat flux traces for an unsustained flame spread case are shown. The three lowest heat flux gages (at heights of 10, 28, and 50 cm) reached a maximum forward heat flux of 30 kW/m^2 , but the upper two gages (at heights of 78 and 110 cm) did not reach the maximum level of heat flux because the flames never spread to these heights. The location of the flame tip is denoted in the figure with a circle. Typically, the arrival of the flame tip indicates an increase in heat feedback to the surface due to flames now covering the surface, and the effect may be seen in each of the heat flux gage trace figures. Fig. 13 was constructed from data in which the flame spread was *nearly* sustained and Fig. 14 is based on data in which the flame spread was sustained to the top of the sample. Note that the

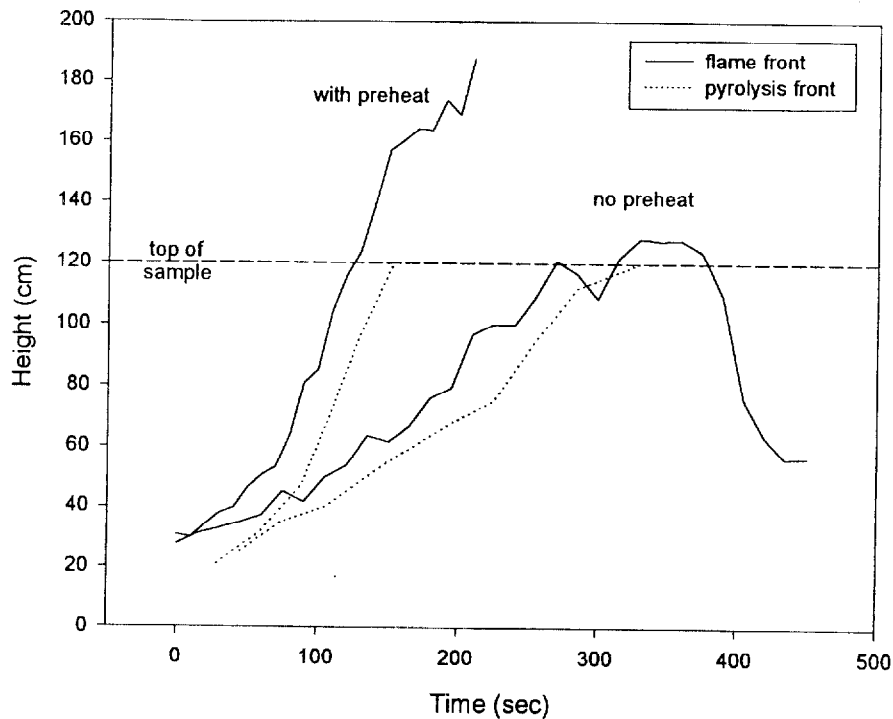


Fig. 10. Effect of preheat on flame spread, particle board, external radiation of 2.2 kW/m^2 , igniter at 18.5 kW/m .

flame spread rate is higher in Fig. 14 because a higher external radiation was used. In Fig. 13, the highest gage did not reach the maximum heat flux level until about 400 s. The highest gage for the test shown in Fig. 14 reached the maximum heat flux level at 80 s. For all heat flux data shown, each of the gages reached a fairly constant level of heat flux as the flame passed and remained at this level until the flame began to recede. The trends seen in the heat flux gage data have been reported for plywood samples [14].

Looking at the three graphs of heat flux gage traces, an average plateau level heat flux may be obtained for the gages. In Figs. 12, 13, and 14 the plateau is around 30, 32, and 45 kW/m^2 , respectively. If the local level of external radiation is subtracted from this value, then all three of the graphs result in a maximum forward heat flux, due to the flames alone, of about 30 kW/m^2 . The heat flux gage data shown in Figs. 12–14 are from burn events on 15.9 mm thick particle board. Similar heat flux gage traces were obtained for the other materials examined in the series of experiments and the maximum forward heat flux for each material is listed in Table 1. The data for the maximum forward heat feedback for PMMA reported was taken from Kim [3]. Tests

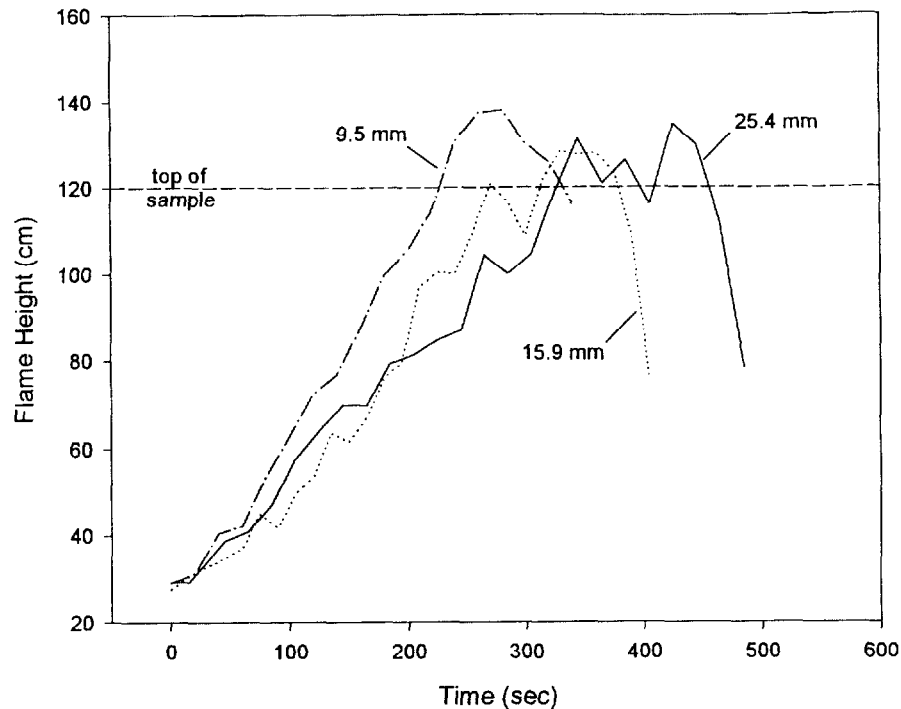


Fig. 11. Effect of thickness on flame spread on particle board, external radiation of 2.2 kW/m^2 , igniter at 18.5 kW/m^2 , no preheat.

on plywood [14] measured an average peak heat flux of 33.5 kW/m^2 when the level of supplied radiant flux was subtracted. This is in good agreement with the 35 kW/m^2 value of maximum forward heat flux obtained for plywood in this work. The work by Delichatsios *et al.* [14] showed the maximum forward heat flux increased slightly as the level of supplied external radiation was increased. Selecting a single value of maximum forward heat feedback may be an approximation and further work may be required to determine a more exact relationship. Nevertheless, maximum forward heat feedback may prove to be a useful criterion for ranking the flammability of materials and for use in numerical models of upward flame spread such as the equation given in the opening of the paper.

A second column in Table 1 shows the level of external radiation that was required in order to sustain flame spread to the top of the sample. Samples with higher levels of maximum forward heat flux tend to require lower levels of external radiation in order for sustained flame spread to occur. Since the data contain mainly wood-based samples (except for PMMA), it is not possible to comment on the strength of this trend.

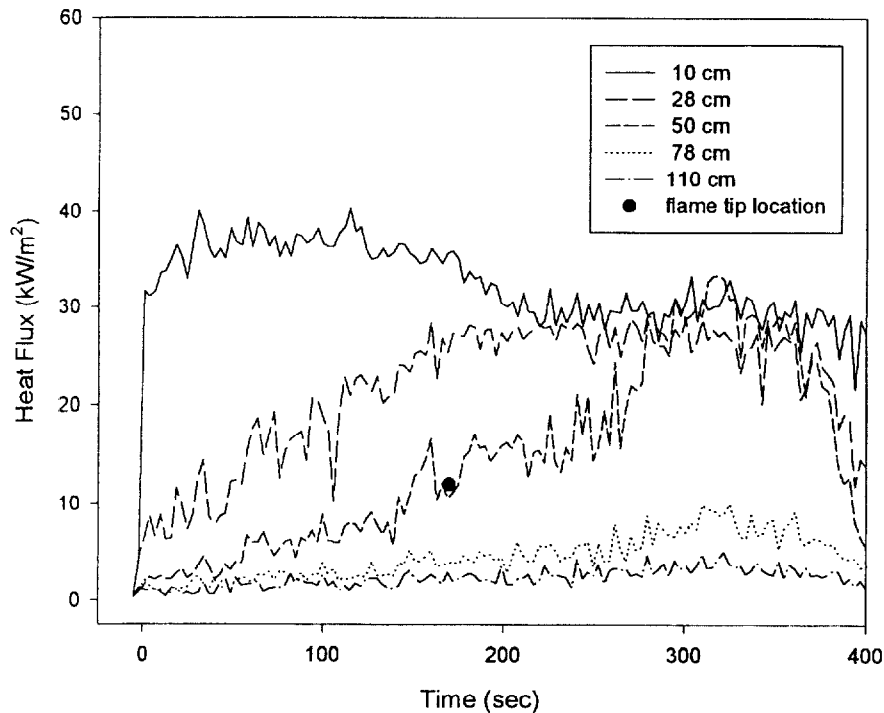


Fig. 12. Heat flux gage data for an unsustained flame spread case for 15.9 mm particle board with $<0.5 \text{ kW/m}^2$ of external radiation.

4. Summary and conclusions

Experimental measurement of flame spread with external radiation was made for various materials (particle board, plywood, cotton textile, poplar, hardboard, cardboard, and PMMA). A moderate level of radiant flux supplied ($5\text{--}10 \text{ kW/m}^2$) was capable of causing sustained upward flame spread for certain materials and enhanced the flame spread rate at flux levels above the critical level. The data may be useful for validation of upward flame spread models.

A characteristic maximum forward heat feedback was measured for several of the samples tested. The information may be useful for assessing the flammability of a material in upward flame spread situations and for input into simplified flame spread models.

It was shown that increasing line burner strength caused flames to spread to higher levels, but does not to cause flame spread to be sustained. Preheating the sample at moderate levels of external radiation resulted in a decrease in the level of external radiation required to sustain upward flame spread, and, over the range of particle board thicknesses tested, the flame spread rate was slightly affected by the thickness.

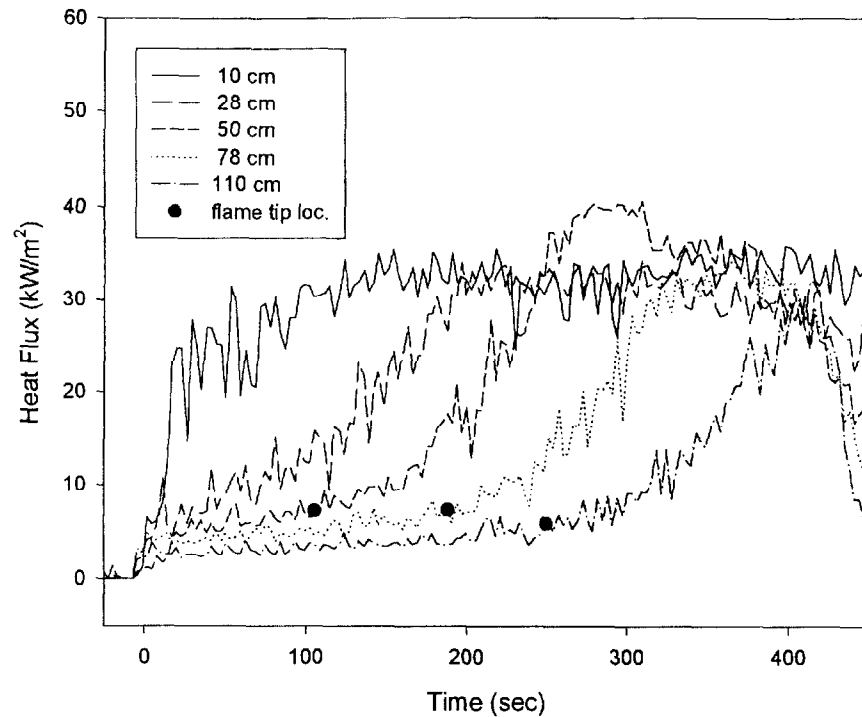


Fig. 13. Heat flux gage data for a nearly sustained flame spread case for 15.9 mm particle board with 2.2 kW/m^2 of external radiation.

Table 1

Maximum forward heat feedback and critical radiant flux for sustained flame spread for various materials

Material	Maximum forward heat flux (kW/m^2)	Crit. rad. flux for sustained flame spread (kW/m^2)
Hardboard	49	0
Poplar	43	2.2
Polymethylmethacrylate [3]	35	0
Plywood	35	7.6
Cardboard	35	7.6
Particle board	32	7.6

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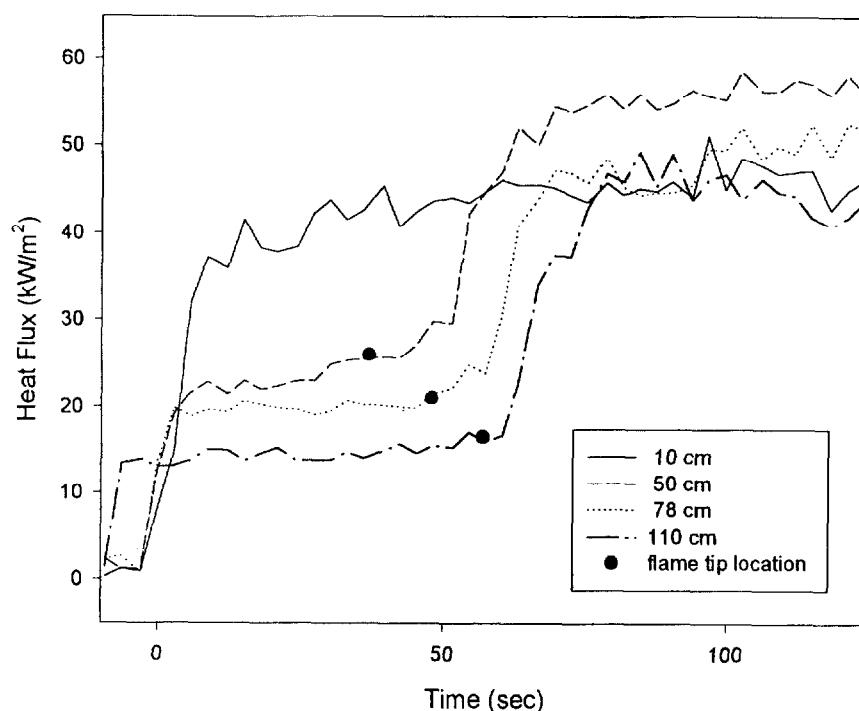


Fig. 14. Heat flux gage data for a fast, sustained flame spread case for 15.9 mm particle board with 13.5 kW/m² of external radiation.

References

- [1] Orloff L, deRis J, Markstein GH. Upward turbulent fire spread and burning of a fuel surface. Proc 15th Symp on Combustion. The Combustion Institute, Pittsburgh, PA, 1975:183–192.
- [2] Saito K, Quintiere JG, Williams FA. Upward turbulent flame spread. Fire safety science. Proc 1st Int Symp. 1986:75–86.
- [3] Kim CI. Upward flame spread on vertical walls. Ph.D. thesis. Pennsylvania State University, University Park, PA, 1991.
- [4] Babrauskas V. North American experiences in the use of the cone calorimeter data for classification of products. In: EURIFIC performance-based reaction to fire classification, Int Seminar, Copenhagen, Denmark, 11–12 September, London: Interscience, 1991:89–103.
- [5] Saito K, Williams FA, Wichman IS, Quintiere JG. Upward turbulent flame spread on wood under external radiation. J Heat Transfer 1989;111:438–45.
- [6] Fernandez-Pello AC. Upward laminar flame spread under the influence of externally applied thermal radiation. Combust Sci Technol, 1977;17:87–98.
- [7] Annamalai K, Sibulkin M. Ignition and flame spread tests of cellular plastics. J Fire Flammability 1978;9:445–58.
- [8] ASTM E 162. Standard test method for surface flammability of materials using a radiant heat energy source. American Society of Testing and Materials 1987.
- [9] ASTM E 648. Standard test method for critical radiant flux of floor-covering systems using a radiant heat energy source. American Society of Testing and Materials, 1988.

- [10] Thomas PH, Lawson DI. Some experiments on the burning of fabrics and the heights of bouyant diffusion flames. Joint Fire Research Organization, Borehamwood, UK., Fire Research Note 420, 1960.
- [11] Kokkala M, Baroudi D, Parker WJ. Upward flame spread on wooden surface products: experiments and numerical modelling. In: fire safety science, Proc 5th Int Symp. 1997:309–20.
- [12] Quintiere JG, Harkleroad M, Hasemi Y. Wall flames and implications for upward flame spread. Combust Sci Technol 1986;48:191–222.
- [13] Hasemi Y, Yoshida M. U.S.–Japan cooperative wall fire experiment and related projects. In: First Interim and Internal Report. October 1990.
- [14] Delichatsios MM, Wu P, Delichatsios MA, Lougheed GD, Crampton GP, Qian C, Ishida H, Saito K. Effect of external radiant heat flux on upward fire spread: measurements on plywood and numerical predictions. Fire safety science, Proc 4th Int Symp. 1994:421–32.